

Lepton-Flavored Electroweak Baryogenesis

Huai-Ke Guo,^{1,2} Ying-Ying Li,³ Tao Liu,³ Michael Ramsey-Musolf,^{1,4} and Jing Shu^{2,5}

¹*Amherst Center for Fundamental Interactions, Department of Physics,
University of Massachusetts Amherst, Amherst, MA 01003, USA*

²*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics,
Chinese Academy of Sciences, Beijing 100190, China*

³*Department of Physics, The Hong Kong University of Science and Technology,
Clear Water Bay, Kowloon, Hong Kong S.A.R., P.R.C.*

⁴*Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, CA 91125 USA*

⁵*CAS Center for Excellence in Particle Physics, Beijing 100049, China*

We explore lepton-flavored electroweak baryogenesis, driven by CP-violation in leptonic Yukawa sector, using the $\tau - \mu$ system in the two Higgs doublet model as an example. This setup generically yields, together with the flavor-changing decay $h \rightarrow \tau\mu$, a tree-level Jarlskog-invariant that can drive dynamical generation of baryon asymmetry during a first-order electroweak phase transition and results in CP-violating effect in the decay $h \rightarrow \tau\tau$. We find that the observed baryon asymmetry can be generated in parameter space compatible with current experimental results for the decays $h \rightarrow \tau\mu$, $h \rightarrow \tau\tau$ and $\tau \rightarrow \mu\gamma$, as well as the present bound on the electric dipole moment of the electron. The baryon asymmetry generated is intrinsically correlated with the CP-violating decay $h \rightarrow \tau\tau$ and the flavor-changing decay $h \rightarrow \tau\mu$, which thus may serve as “smoking guns” to test lepton-flavored electroweak baryogenesis.

Introduction. Explaining the origin of the baryon asymmetry of the universe (BAU) is a forefront challenge for fundamental physics. The BAU is characterized by the baryon density n_B to entropy s ratio

$$Y_B = \frac{n_B}{s} = (8.61 \pm 0.09) \times 10^{-11} \quad [1]. \quad (1)$$

According to Sakharov [2], generation of a non-vanishing Y_B requires three ingredients in the particle physics of the early universe: non-conservation of baryon number (B); C- and CP-violation (CPV); and out of equilibrium dynamics (assuming CPT conservation). While the Standard Model (SM) of particle physics contains the first ingredient in the guise of electroweak sphalerons, it fails with regard to the remaining two. Physics beyond the SM is, thus, essential for successful baryogenesis.

Electroweak baryogenesis (EWBG)[3] is among the most theoretically well-motivated and experimentally testable scenarios, as it ties BAU generation to electroweak symmetry-breaking (see [4] for a recent review). Extending the SM scalar sector can lead to a first order electroweak phase transition(EWPT), thereby satisfying the out-of-equilibrium condition. Addressing the second Sakharov criterion requires new sources of CPV, as the effect of CPV in the SM Yukawa sector is suppressed by the small magnitude of the Jarlskog invariant associated with the Cabbibo-Kobayashi-Maskawa (CKM) matrix and by the small quark mass differences relative to the electroweak temperature, $T_{EW} \sim 100$ GeV.

It is possible that an extended Yukawa sector may remedy this SM shortcoming. A particularly interesting yet unexplored possibility involves the leptonic Yukawa interactions. Phenomenologically, the report by the CMS collaboration of a signal for the charged lepton flavor violating (CLFV) Higgs boson decay $h \rightarrow \tau\mu$ (2.4 σ

significance)[8] hints at a possible richer leptonic Yukawa sector [9], though the ATLAS collaboration observes no evidence for this decay mode[10]. Should an extended leptonic Yukawa sector exist, then the accompanying new CPV phases may provide sources for EWBG that do not suffer from the suppression associated with SM quark Yukawa sector.

Motivated by these considerations, we study the viability of “lepton flavored EWBG”, a scenario that relies on both CLFV and leptonic CPV. For concreteness, we use a variant of the type III two Higgs doublet model (2HDM) [15] with generic leptonic Yukawa textures [16] and focus on the $\tau - \mu$ families as an example. For a representative choice of Yukawa texture, we derive the CPV source for the EWBG quantum transport equations [11, 13] in terms of the relevant Jarlskog invariant, $\text{Im}J_A$. We then solve these equations, which encode the dynamics of CLFV scattering during the electroweak phase transition, and obtain the BAU as a function of the Yukawa matrix parameters. We also show that the same $\text{Im}J_A$ also generates a CPV coupling of the Higgs boson to τ leptons at $T = 0$, parameterized by a CPV phase ϕ_τ . Measurements of CPV asymmetries in $h \rightarrow \tau^+\tau^-$, as discussed in Ref. [14], would provide a test of this baryogenesis mechanism. Taking into account present constraints from measurements of $\Gamma(h \rightarrow \tau^+\tau^-)$ and limits on $\Gamma(\tau \rightarrow \mu\gamma)$ we find that a $\mathcal{O}(10^\circ)$ determination of ϕ_τ would probe this scenario at a significant level.

Model Setup. Since our focus is on CPV in the $\mu - \tau$ sector which has no mixing with the first-generation charged leptons, we assume the scalar potential to be CP-conserving with parameters chosen to generate a strongly first order EWPT [25]. The particle spectrum consists of two CP-even neutral scalars (h, H), the neutral CP-odd A , and a pair of charged scalars H^\pm , with the lighter h

taken to be SM-like. The $SU(2)_L \times U(1)_Y$ invariant weak eigenbasis lepton Yukawa interaction is

$$\mathcal{L}_{\text{Yukawa}}^{\text{Lepton}} = -\bar{L}^i [Y_{1,ij} \Phi_1 + Y_{2,ij} \Phi_2] e_R^j + \text{h.c.}, \quad (2)$$

where $\Phi_{1,2}$ are the two Higgs doublets with the same hypercharge, L^i and e_R^j are left-handed lepton doublet and right-handed lepton singlet in weak basis, with the family index $i, j = 2, 3$. Then we can uniquely define a Jarlskog invariant as the imaginary part of [19, 20]:

$$J_A = \frac{1}{v^2 \mu_{12}^{\text{HB}}} \sum_{a,b,c=1}^2 v_a v_b^* \mu_{bc} \text{Tr} [Y_c Y_a^\dagger], \quad (3)$$

with the power of Yukawa coupling (or mass parameter of fermions) product being two. Here $v_a = \sqrt{2} \langle \Phi_a^0 \rangle$ is vacuum expectation value (vev) of neutral Higgs fields, μ_{ab} is the coefficient of $\Phi_a^\dagger \Phi_b$ in the potential, and the trace is taken over flavor space. J_A is normalized to be a dimensionless quantity by dividing a factor $v^2 \mu_{12}^{\text{HB}}$, where

$$\mu_{12}^{\text{HB}} = \frac{1}{2} (\mu_{22} - \mu_{11}) \sin 2\beta + \mu_{12} \cos 2\beta \quad (4)$$

is a quadratic Higgs coupling defined in ‘‘Higgs basis’’ [15, 20]: $H_1 = \cos \beta \Phi_1 + \sin \beta \Phi_2$; $H_2 = -\sin \beta \Phi_1 + \cos \beta \Phi_2$; $\langle H_1^0 \rangle = v/\sqrt{2} = 174$ GeV; and $\langle H_2^0 \rangle = 0$.

The mass matrix for fermions is defined as

$$M = (v_1 Y_1 + v_2 Y_2)/\sqrt{2} \quad (5)$$

in the weak basis, with a determinant of $M^\dagger M$ or M close to zero (since $m_\mu \approx 0$). For illustration, we choose a texture with $Y_{j,22} = Y_{j,23} \equiv 0$, with $j = 1, 2$. This immediately yields

$$\text{Im}(J_A) = -\text{Im}(Y_{1,32} Y_{2,32}^* + Y_{1,33} Y_{2,33}^*) \quad (6)$$

or

$$\text{Im}(J_A) = -\text{Im}(Y_{1,32} Y_{2,32}^*), \quad (7)$$

with a further assumption $Y_{1,33} = Y_{2,33}$. The diagonalization condition $|M_{32}|^2 + |M_{33}|^2 = m_\tau^2$ immediately gives $|M_{32}| \leq m_\tau$, and fixes the value of $|Y_{1,33}| = |Y_{2,33}|$. Since the proposed mass texture is not invariant under basis transformation of Φ_1 and Φ_2 , $\tan \beta = v_2/v_1$ becomes an independent parameter (similar to what happens in type II 2HDM). Thus this setup contains five relevant and independent parameters: $\tan \beta$, α (the mixing angle in the CP-even Higgs sector), $|Y_{2,32}|$, $r_{32} = |Y_{1,32}|/|Y_{2,32}|$ and $\text{Im}(J_A)$.

In the mass basis for both fermions and Higgs bosons, the τ Yukawa interaction is then parameterized as

$$-\frac{1}{v} \bar{\tau}_L \tau_R [h(m_\tau s_{\beta-\alpha} + N_{\tau\tau} c_{\beta-\alpha}) + H(m_\tau c_{\beta-\alpha} - N_{\tau\tau} s_{\beta-\alpha}) + i A N_{\tau\tau}] + \text{h.c.}, \quad (8)$$

where $\beta - \alpha$ is invariant under the basis transformation in Higgs family space [18]. The SM-like Higgs boson h

receives two contributions to its coupling. The first one results from its H_1^0 component which is aligned with the τ mass. Another one is related to its H_2^0 component which is proportional to $N_{\tau\tau}$, the Yukawa coupling of H_2^0 with τ leptons, with

$$\begin{aligned} \text{Re}(N_{\tau\tau}) &= \frac{v^2 \mu_{12}^{\text{HB}} \text{Re}(J_A) - 2\mu_{11}^{\text{HB}} m_\tau^2}{2\mu_{12}^{\text{HB}} m_\tau}, \\ \text{Im}(N_{\tau\tau}) &= \frac{v^2 \text{Im}(J_A)}{2m_\tau}. \end{aligned} \quad (9)$$

The CLFV interactions are completely controlled by the Yukawa coupling of H_2^0 , $N_{\tau\mu}$,

$$-\frac{N_{\tau\mu}}{v} \bar{\tau}_L \mu_R (c_{\beta-\alpha} h - s_{\beta-\alpha} H + i A) + \text{h.c.}, \quad (10)$$

With $\tan \beta = 1$, the expression in terms of weak basis parameters is given by

$$N_{\tau\mu} = e^{i\delta} \left| N_{\tau\tau} \frac{M_{33}}{M_{32}} \right|. \quad (11)$$

Here δ is an un-physical phase undetermined in the diagonalization procedure which can be removed by field redefinition. For later convenience, we also have for $\tan \beta = 1$

$$\text{Re}(J_A) = \frac{1}{2} (|Y_{2,32}|^2 - |Y_{1,32}|^2) + \frac{2m_\tau^2 \mu_{11}^{\text{HB}}}{v^2 \mu_{12}^{\text{HB}}}. \quad (12)$$

Finally the charged Higgs Yukawa interactions are governed by $-\sqrt{2}/v H^\pm \bar{\nu}_L^i N_{ij} e_R^j + \text{h.c.}$

Given the four free parameters left for describing tree-level Yukawa interactions of the $\mu - \tau$ system, we present various phenomenological results (e.g., $h \rightarrow \tau\tau, \tau\mu$ and $\tau \rightarrow \mu\gamma$ constraints) and the BAU analysis in terms of the effective $h\bar{\tau}\tau$ coupling [37] (see Fig. 1)

$$-\frac{m_\tau}{v} [\text{Re}(y_\tau) \bar{\tau}\tau + \text{Im}(y_\tau) \bar{\tau} i \gamma_5 \tau] h \quad (13)$$

with benchmark values assigned to r_{32} and $\beta - \alpha$. Here

$$\begin{aligned} \text{Re}(y_\tau) &= s_{\beta-\alpha} + \frac{c_{\beta-\alpha}}{m_\tau} \text{Re}(N_{\tau\tau}), \\ \text{Im}(y_\tau) &= \frac{c_{\beta-\alpha}}{m_\tau} \text{Im}(N_{\tau\tau}). \end{aligned} \quad (14)$$

Then, the condition $|M_{32}| \leq m_\tau$ imposes a constraint at the $(\text{Re}(y_\tau), \text{Im}(y_\tau))$ plane, allowing only a circular region centered at $(\text{Re}(y_\tau) = s_{\beta-\alpha} + c_{\beta-\alpha}(1+r_{32}^2)/(1-r_{32}^2), \text{Im}(y_\tau) = 0)$ with a radius $2|c_{\beta-\alpha} r_{32}|/(1-r_{32}^2)$. At its boundary, we have $M_{33} = 0$ and hence $N_{\tau\mu} = 0$. For $r_{32} = 1$, $N_{\tau\tau}$ is purely imaginary, yielding a vertical line at $\text{Re}(y_\tau) = s_{\beta-\alpha}$. In Fig. 1, we present results in two representative cases: $r_{32} = 0.9$ and $r_{32} = 1.1$, with $\beta - \alpha - \frac{\pi}{2} = 0.05$.

$h \rightarrow \tau\tau$ constraints. The decay width for $h \rightarrow \tau\tau$ is given by

$$\Gamma^{\tau\tau} = \frac{\sqrt{2} G_F m_h m_\tau^2}{8\pi} |y_\tau|^2. \quad (15)$$

Experimentally, the ATLAS signal strength is $\mu_{\text{ATLAS}}^{\tau\tau} = 1.43_{-0.37}^{+0.43}$ [34] while CMS favors a smaller one $\mu_{\text{CMS}}^{\tau\tau} = 0.78 \pm 0.27$ [35]. We take a χ^2 analysis at 95% C.L. for these two measurements, assuming a Gaussian distribution for both and neglecting their correlations. Apparently, the allowed parameter region should be a circular band at the $(\text{Re}(y_\tau), \text{Im}(y_\tau))$ plane, as is indicated by two green dashed curves in Fig. 1. A future determination of this coupling that agrees with the SM value within $\pm 10\%$ is plotted as a curved blue band.

$h \rightarrow \tau\mu$ constraints. The lepton flavor-changing decay width is given by

$$\Gamma^{\tau\mu} = \frac{\sqrt{2}c_{\beta-\alpha}^2 G_F m_h}{8\pi} |N_{\tau\mu}|^2. \quad (16)$$

Theoretically, a sizable $\text{Br}(h \rightarrow \tau\mu)$ requires a small $|M_{32}|$ (see Eq. (11)). ATLAS sets an upper limit on its branching ratio, $\text{Br}(h \rightarrow \tau\mu) < 1.43\%$, at 95% C.L. [10], while CMS gives a best fit $\text{Br}(h \rightarrow \tau\mu) = 0.84_{-0.37}^{+0.39}\%$ as well as an upper limit $\text{Br}(h \rightarrow \tau\mu) < 1.51\%$ at 95% C.L. [8]. In Fig. 1, the current ATLAS upper limit 1.43% as well as two projected ones, say, 1% and 0.5%, are shown as dashed curves, in the two cases with $r_{32} = 0.9$ and 1.1. The circular boundaries of the brown regions correspond to vanishing M_{33} or $N_{\tau\mu}$, yielding $\text{Br}(h \rightarrow \tau\mu) = 0$.

$\tau \rightarrow \mu\gamma$ constraints. Non-vanishing $N_{\tau\mu}$ may also contribute to the rare decay $\tau \rightarrow \mu\gamma$, via one-loop neutral and charged Higgs mediated diagrams and two-loop Barr-Zee type diagrams [32, 33]. Explicitly, one has

$$\text{Br}(\tau \rightarrow \mu\gamma) = \frac{\tau_\tau \alpha G_F^2 m_\tau^5}{32\pi^4} (|C_{7L}|^2 + |C_{7R}|^2), \quad (17)$$

where $\tau_\tau = (290.3 \pm 0.5) \times 10^{-15} \text{s}$ [30] is the τ lifetime and $C_{7L/R}$ are the Wilson coefficients of the dipole operators

$$Q_7^{L/R} = \frac{e}{8\pi^2} m_\tau \bar{\mu} \sigma^{\mu\nu} (1 \mp \gamma^5) \tau F_{\mu\nu}, \quad (18)$$

in the Hamiltonian $-G_F [C_{7L} Q_7^L + C_{7R} Q_7^R] / \sqrt{2}$ [31]. In our setup, C_{7L} and C_{7R} are proportional to $N_{\tau\mu}^*$ and $N_{\mu\tau}$, respectively, yielding a vanishing C_{7R} . The current experimental limit is $\text{Br}(\tau \rightarrow \mu\gamma) < 4.4 \times 10^{-8}$ (90% C.L.) [29]. The allowed parameter regions are denoted in gray in Fig. 1. Obviously there exists a positive correlation between the experimental constraints from $\text{Br}(h \rightarrow \tau\mu)$ and $\text{Br}(\tau \rightarrow \mu\gamma)$, though the relevant new physics contributions result from tree- and loop-levels, respectively.

Electric dipole moments. Null results from experimental searches for the electric dipole moments (EDMs) of the neutron, neutral atoms, and molecules in general place stringent limits on new sources of CPV. In the present instance, the electron EDM (d_e) provides the most significant probe of $\text{Im}(J_A)$ or $\text{Im}y_\tau$, given the bound obtained by the ACME collaboration using

ThO [42]. In our setup, the dominant contribution to electron EDM results from h -mediated Barr-Zee diagram with a τ lepton loop, because of non-vanishing $\text{Im}y_\tau$. We find $|d_e/e| \approx 1.66 \times 10^{-29} |\text{Im}y_\tau| \text{cm}$, yielding a bound of $|\text{Im}y_\tau| < 5.2$. As indicated in Fig. 1, this bound is an order of magnitude larger than what is required to account for the observed BAU (see below). We also note in passing that CPV in the scalar potential, associated with a different Jarlskog invariant, will lead to mixing between the CP-even and CP-odd scalars. The resulting EDM contributions can be considerably larger (for a given value of the relevant Jarlskog invariant). For a recent analysis, see Ref. [36].

Electroweak baryogenesis. The first order EWPT proceeds via bubble nucleation. CPV scattering from the bubble walls generates a net left-handed fermion density n_L , whose diffusion ahead of the advancing wall biases the electroweak sphalerons into producing a net baryon number density, n_B . The expanding bubbles capture and preserve this density if the sphaleron processes are sufficiently quenched inside the bubbles. We compute n_L from a set of quantum transport equations, derived from the equations of motion for Wightman functions arising in the closed time path formulation of non-equilibrium quantum field theory by expanding in gradients of the bubble wall profile and chemical potentials (see Ref. [13] for pedagogical discussions). As with earlier work, we will employ the “vev insertion approximation”, which provides a reasonable estimation of the CPV sources (see Ref. [4] for a discussion of theoretical issues associated with the computation of these sources), and work in fermion weak basis (i.e. approximate fermion mass basis during EWPT) in this section. Since the weak sphaleron rate Γ_{ws} [28] is much smaller than the rates for diffusion and particle number changing reactions that govern n_L [40], we first solve for this density and substitute the result into the equation for n_B .

For simplicity, we neglect bubble wall curvature [21], so that the quantities entering the quantum transport equations depend only on the coordinate in the bubble wall rest frame $\bar{z} = z + v_w t$ with v_w being the wall velocity, $\bar{z} > 0$ corresponding to broken phase and $\bar{z} < 0$ for unbroken phase. Since non-zero densities for the first and second generation quarks as well as for the bottom quark are generated only by strong sphaleron processes, the following relations hold: $Q_1 = Q_2 = -2U = -2D = -2C = -2S = -2B$, where Q_k denotes the density of left-handed quarks of generation k and $U, D, \text{etc.}$ denote the corresponding right-handed quark densities. In addition, $L_1 = L_2 = e_R \approx 0$ since the corresponding leptonic Yukawa interactions are negligible compared to those retained in our choice of Yukawa texture. Local baryon number density is also approximately conserved on the time scales relevant to the reactions that govern n_L , so that $\sum_{i=1}^3 (Q_i + U_i + D_i) = 0$. The resulting trans-

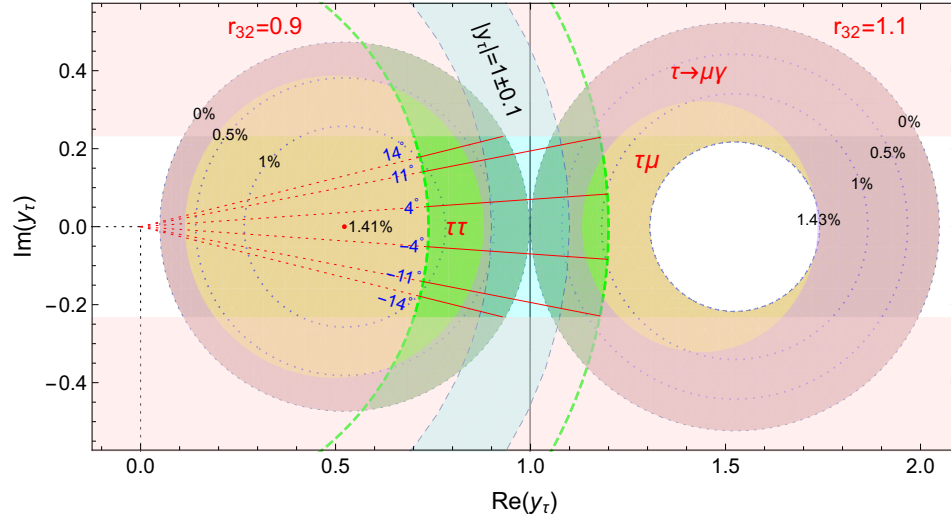


FIG. 1. Theoretical and phenomenological constraints on the Higgs- τ Yukawa couplings in Eq. (13). The inner parts of circular regions satisfy the diagonalization constraint $|M_{32}| \leq m_\tau$ for two representative choices of r_{32} , with the outer boundaries giving vanishing $\text{Br}(\tau \rightarrow \mu\gamma)$ and $\Gamma(h \rightarrow \tau\mu)$. The $r_{32} = 0.9$ and $r_{32} = 1.1$ regions are separated by the vertical dashed line at $\text{Re}(y_\tau) = \sin(0.05 + \frac{\pi}{2}) \approx 1$. Brown regions correspond to non-vanishing $\Gamma(h \rightarrow \tau\mu)$, with different representative values (1%, 0.5% and 0%) indicated by circular dashed lines. For $r_{32} = 1.1$, the ATLAS 95% C.L. upper bound of 1.43% is shown, while for $r_{32} = 0.9$ a maximum BR of 1.41% can be achieved within the theoretically allowed region. Upper limits on $\Gamma(h \rightarrow \tau\tau)$ (95% C.L.) and $\text{Br}(\tau \rightarrow \mu\gamma)$ (90% C.L.) are given by the green and grey regions, respectively. The region inside the green dashed lines gives the Higgs signal strength $\mu^{\tau\tau}$ allowed region at 95% C.L. without assuming a specific Yukawa texture. The inner light-blue band labelled $|y_\tau| = 1 \pm 0.1$ corresponds to the region with a more SM-like $h\bar{\tau}\tau$ coupling. The region giving the observed BAU is indicated by the horizontal pink bands assuming $|\Delta\beta| \leq 0.4$ for $\beta - \alpha - \frac{\pi}{2} = 0.05$ as discussed in the text. The other relevant parameters are fixed to be $m_H = m_A = m_{H^\pm} = 500\text{GeV}$, $v_w = 0.05$, $L_W = 2/T$, $D_q = 6/T$ and $T = 100\text{GeV}$. To guide the eye, the argument of y_τ is indicated with red-dotted lines. Note, the calculation of baryon asymmetry outside the circular regions could be unreliable due to the breaking of perturbative “mass insertion”.

port equations are

$$\begin{aligned}
 \partial_\mu Q_3^\mu &= \Gamma_{mt}(\xi_T - \xi_{Q_3}) + \Gamma_t(\xi_T - \xi_H - \xi_{Q_3}) \\
 &\quad + 2\Gamma_{ss}\delta_{ss}, \\
 \partial_\mu H &= \Gamma_t(\xi_T - \xi_H - \xi_{Q_3}) + \Gamma_\tau(\xi_{L_3} - \xi_{\tau_R} - \xi_H) \\
 &\quad - 2\Gamma_h\xi_H, \\
 \partial_\mu L_3^\mu &= -\Gamma_{m\tau}(\xi_{L_3} - \xi_{\tau_R}) - \Gamma_\tau(\xi_{L_3} - \xi_{\tau_R} - \xi_H) \\
 &\quad + S_{\tau_L}^{CPV}, \\
 \partial_\mu \tau_R^\mu &= -\Gamma_\tau(\xi_H + \xi_{\tau_R} - \xi_{L_3}) + \Gamma_{m\tau}(\xi_{L_3} - \xi_{\tau_R}), \\
 \partial_\mu T^\mu &= -\Gamma_{mt}(\xi_T - \xi_{Q_3}) - \Gamma_t(\xi_T - \xi_H - \xi_{Q_3}) \\
 &\quad - \Gamma_{ss}\delta_{ss}, \\
 \partial_\mu \mu_R^\mu &= S_{\mu_R}^{CPV},
 \end{aligned} \tag{19}$$

where $\delta_{ss} = \xi_T + 9\xi_B - 2\xi_{Q_3}$, $\xi_a = n_a/k_a$, with k_a being the statistical weight [13] associated with the number density n_a of species “a” and $\partial_\mu \approx v_w \frac{d}{d\bar{z}} - D_a \frac{\partial^2}{\partial \bar{z}^2}$ with D_a being the diffusion constant [22] from the diffusion approximation. The CPV source terms are

$$S_{\tau_L}^{CPV} = -S_{\mu_R}^{CPV} = \frac{v^2(\bar{z})v_w \frac{d\beta(\bar{z})}{d\bar{z}} \text{Im}(J_A)}{2\pi^2} \mathcal{I}, \tag{20}$$

where \mathcal{I} is a momentum-space integral that depends on the leptonic thermal masses (see Ref. [23]) and $d\beta/d\bar{z}$ characterizes the local variation of $\tan\beta(\bar{z})$ as one moves

across the bubble wall. Furthermore $\Gamma_{ss} \approx 16\alpha_s^4 T$ is the strong sphaleron rate [24]; Γ_{mt} is the two body top relaxation rate [13]; and $\Gamma_{t/\tau}$ is the t/τ Yukawa induced three body rate [26]. After solving for the densities in Eqs. (19), we obtain $n_L = \sum_i (Q_i + L_i)$ [27] and n_B , which is a constant in the broken phase:

$$n_B = \frac{3\Gamma_{ws}}{D_q\lambda_+} \int_0^{-\infty} n_L(\bar{z}) e^{-\lambda_- \bar{z}} d\bar{z}, \tag{21}$$

where $\Gamma_{ws} \approx 120\alpha_w^5 T$ [28] and $\lambda_\pm = (v_w \pm \sqrt{v_w^2 + 15\Gamma_{ws}D_q})/(2D_q)$.

Assuming a fast τ_R diffusion [41], we solve the transport equations perturbatively at the leading order of Γ_t^{-1} , Γ_y^{-1} , Γ_τ^{-1} and Γ_{ss}^{-1} . We have further neglected $\Gamma_{m\tau}$ in the final result as it is generally small compared with Γ_{mt} ; then n_B is proportional to $\text{Im}(y_\tau)$ with no dependence on $\text{Re}(y_\tau)$. One important remaining parametric uncertainty is the difference of $\beta(\bar{z})$ in the broken and symmetric phases ($\equiv \Delta\beta$) since the CPV source term and thus n_B are both directly proportional to it. Here we take its maximum magnitude to be 0.4 and vary it to obtain the bands in Fig. 1 where the upper and lower bands give opposite signs of BAU resulting from the unknown sign of $\Delta\beta$. Imposing the condition $|M_{32}| < m_\tau$ as discussed above then restricts $\text{Re}(y_\tau)$ to the region of overlap between the pink bands and the two circular regions.

Results and collider probes. Combining the analyses above, we find that there exist parameter regions in Fig. 1 where the observed BAU can be explained without violating current experimental bounds. These regions are characterized by $|\text{Im}(y_\tau)| \gtrsim \mathcal{O}(0.1)$, corresponding to $|\text{Im}(J_A)| \gtrsim \mathcal{O}(10^{-5})$, or $|\phi_\tau| > \mathcal{O}(10^\circ)$. As indicated above, the present EDM upper bounds on these CPV parameters are roughly an order of magnitude larger than the BAU requirements. The next generation searches for neutron, atomic, and molecular EDMs that plan for order of magnitude or better improvements in sensitivities may, thus, begin to probe the BAU-viable parameter space.

Alternatively, collider measurements of the CP properties of the $h\bar{\tau}\tau$ coupling may also test this scenario. For example, a recent study shows that use of the ρ -meson decay plane method or impact parameter method at the LHC may allow a determination of ϕ_τ with an uncertainty of $15^\circ(9^\circ)$ with an integrated luminosity of $150\text{fb}^{-1}(500\text{fb}^{-1})$, or $\sim 4^\circ$ with 3ab^{-1} [37]. At Higgs factories, ϕ_τ could be measured with an accuracy $\sim 4.4^\circ$, with a 250GeV run and 1ab^{-1} luminosity [38]. Therefore, the collider measurements of the CP-properties of the $h\bar{\tau}\tau$ coupling complement the measurements of $h \rightarrow \tau\mu$ or $\tau \rightarrow \mu\gamma$, which constrain more the parameter regions with relatively small $|\text{Im} y_\tau|$, or $|\phi_\tau|$.

Discussion. We stress that $N_{\tau\mu}$ or $N_{\mu\tau}$ are not involved in any Jarlskog invariants here. Indeed, for the Yukawa texture considered in this study, we have $N_{\mu\mu} = N_{\mu\tau} = 0$. Consequently, there is only one independent phase in the $\tau - \mu$ system (apart from an overall common phase), with the corresponding Jarlskog invariant defined by the imaginary part of Eq. (3). This implies that CP-violation in this setup does not affect $y_{\tau\mu}$ or $y_{\mu\tau}$.

With a more generalized texture, the situation can be different [20]. For example, one can define a new Jarlskog invariant [20]

$$\text{Im}(J_B) \sim \text{Im}(\lambda_7^{\text{HB}} N_{\mu\mu} N_{\tau\mu} N_{\mu\tau} m_\tau) \quad (22)$$

with λ_7^{HB} being the coefficient of the term $H_2^\dagger H_2 H_1^\dagger H_2$ in Higgs potential. Here the value of $N_{\mu\mu}$ need not be small, since H_2 does not directly contribute to SM fermion mass generation. Nonetheless, the effects of $\text{Im}(J_B)$ on both $T = 0$ phenomenology and CPV dynamics at finite T arise a loop level, since four instead of two Yukawa couplings (or fermion mass parameters) are involved. Explicitly, $\text{Im}(J_B)$ can be probed via the interference between the tree-level and one-loop diagrams in the decay of $h \rightarrow \mu\tau$. Similarly, $\text{Im}(J_B)$ can contribute the BAU generation at one-loop level, as it enters the one-loop, self-energy correction of fermions that contribute to spacetime-dependent vev scattering, yielding a loop-level CPV source. For similar reasons, its contribution to muon EDM typically requires extra mass insertions, hence being negligibly small. A full exploration in this regard will be deferred to future work.

[Note added] While this article was being finalized, the paper [45] appeared, which partially overlaps with this one in discussing the correlation between electroweak baryogenesis and the $\tau - \mu$ Yukawa structure in the 2HDM. However, in contrast to Ref. [45], we having explicitly show how the baryon asymmetry generated intrinsically correlates with the CP-violating decay $h \rightarrow \tau\tau$, using a Jarlskog invariant uniquely defined at tree level. As for the complex phases of Higgs couplings with τ and μ leptons, which were addressed in Ref. [45], we note that they contribute only to Jarlskog invariants defined as a product of at least four Yukawa couplings (or fermion mass parameters), and hence play a sub-leading role in this exploration generically.

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